Effects of electron beam geometry on pair production in laser-electron scattering

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Motivation

Near future laser facilities will reach peak intensities capable of probing QED effects, e. g. Nonlinear Compton Scattering (γ-ray emission) and Breit-Wheeler e^+e^- pair production.

Accurate predictions of the positron yield in laser-electron scattering require taking into account the laser focusing geometry, which is usually accomplished using full-scale PIC-QED simulations.

For a plane-wave laser with a temporal envelope the total number of new pairs per interacting e^- can be approximated as:

$$N_+^{PW}(\gamma_0, a_0, \lambda, \tau) \simeq 3\sqrt{\frac{\pi}{2}} P_\pm(\omega_c)\ \chi_{c,rr}\ \frac{(\gamma_0 mc^2 - \hbar\omega_c)^2}{\hbar\gamma_0 mc^2} \left.\frac{dN_\gamma}{d\omega}\right|_{\omega=\omega_c}$$

* T. Blackburn, PRA 2017

Extension to a Gaussian laser

Not all electrons will interact with the peak laser field (because of spatio-temporal synchronisation).

Each electron can be assigned $a_{0,\mathrm{eff}} \leq a_0$.

We can use $a_{0,\mathrm{eff}}$ distribution to extend the plane wave model to non-ideal electron beams and focused laser pulses.

$$\frac{\mathrm{d}N_b}{\mathrm{d}a_{0,\mathrm{eff}}} = \frac{2\ n_b\ \mathrm{d}S}{|\nabla a_{0,\mathrm{eff}}|}$$

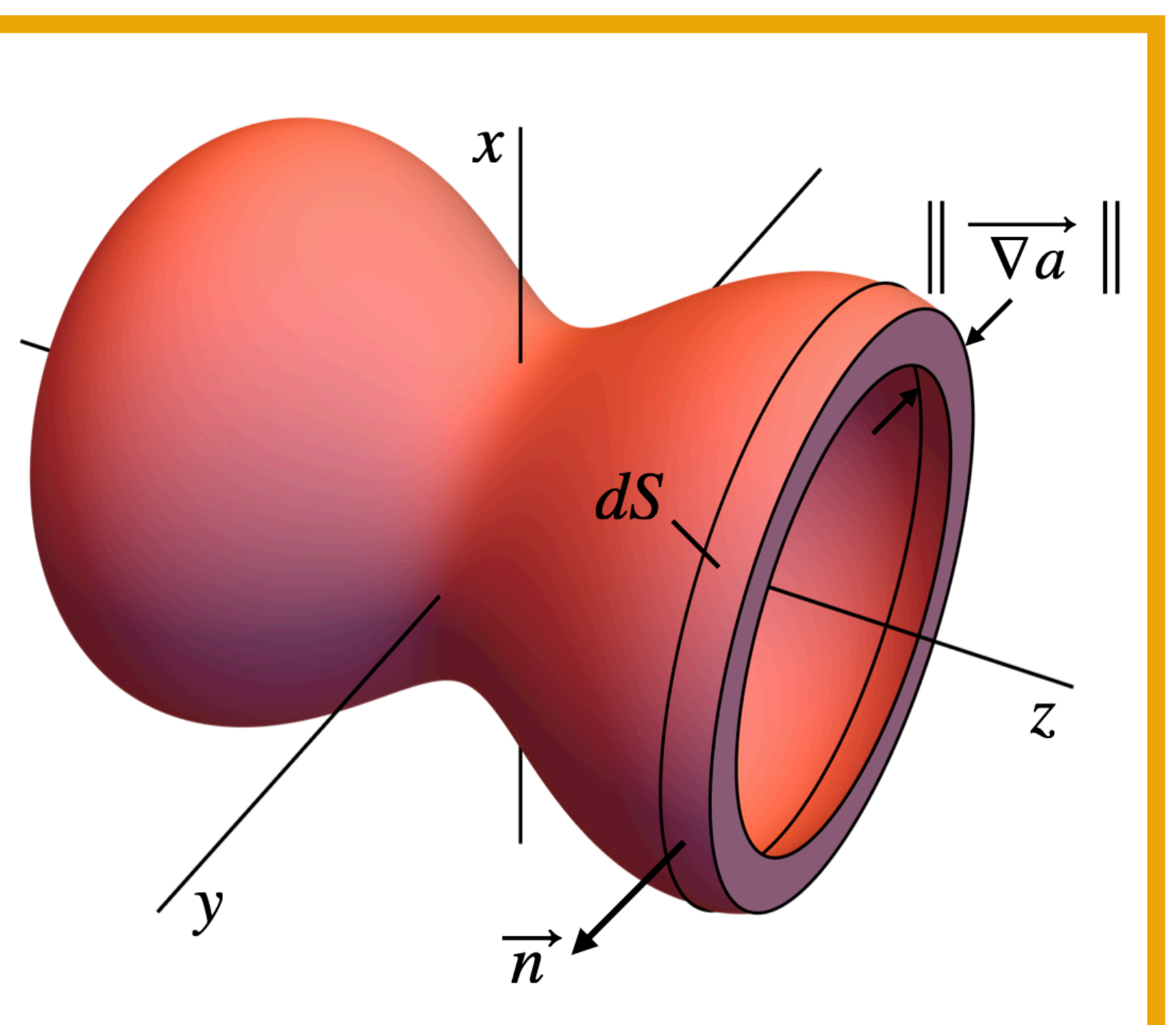

Figure 1: Volume associated with one value of the laser intensity

Peak laser intensity felt by particles within a wide beam

In the scattering between a focused Gaussian laser pulse and a wide electron beam ($R \gg W_0$), the electron distribution according to the maximum a_0 they interact with can be expressed as:

$$\frac{dN_b}{da_{0,\mathrm{eff}}} = \begin{cases} \dfrac{4\pi\ n_b\ W_0^2\ z_R}{a_{0,\mathrm{eff}}} \dfrac{\sqrt{a_0^2 - a_{0,\mathrm{eff}}^2}}{3a_{0,\mathrm{eff}}} \left(2 + \left(\dfrac{a_0}{a_{0,\mathrm{eff}}}\right)^2\right) & , a_{0,\mathrm{eff}} \geqslant a_z \\ \dfrac{4\pi\ n_b\ W_0^2\ z_R}{a_{0,\mathrm{eff}}} \dfrac{L}{4z_R} \left(1 + \left(\dfrac{L}{4z_R}\right)^2\right) & , a_{0,\mathrm{eff}} < a_z \end{cases}$$

, with $a_z \equiv a_0/\sqrt{1 + (L/4z_R)^2}$

The total number of positrons is then $N_+ = \int N_+^{PW}(a_{0,\mathrm{eff}}) \dfrac{\mathrm{d}N_b}{\mathrm{d}a_{0,\mathrm{eff}}}\ \mathrm{d}a_{0,\mathrm{eff}}$

beam : $E_0 = 13$ GeV, $\sigma_x = 24.4\ \mu$m, $\sigma_y = 29.6\ \mu$m, $n_b = 10^{16}$ cm^{-3}
laser : $a_0 = 7.3$, $\lambda = 0.8\ \mu$m, $\tau = 31$ fs, $W_0 = 3\ \mu$m

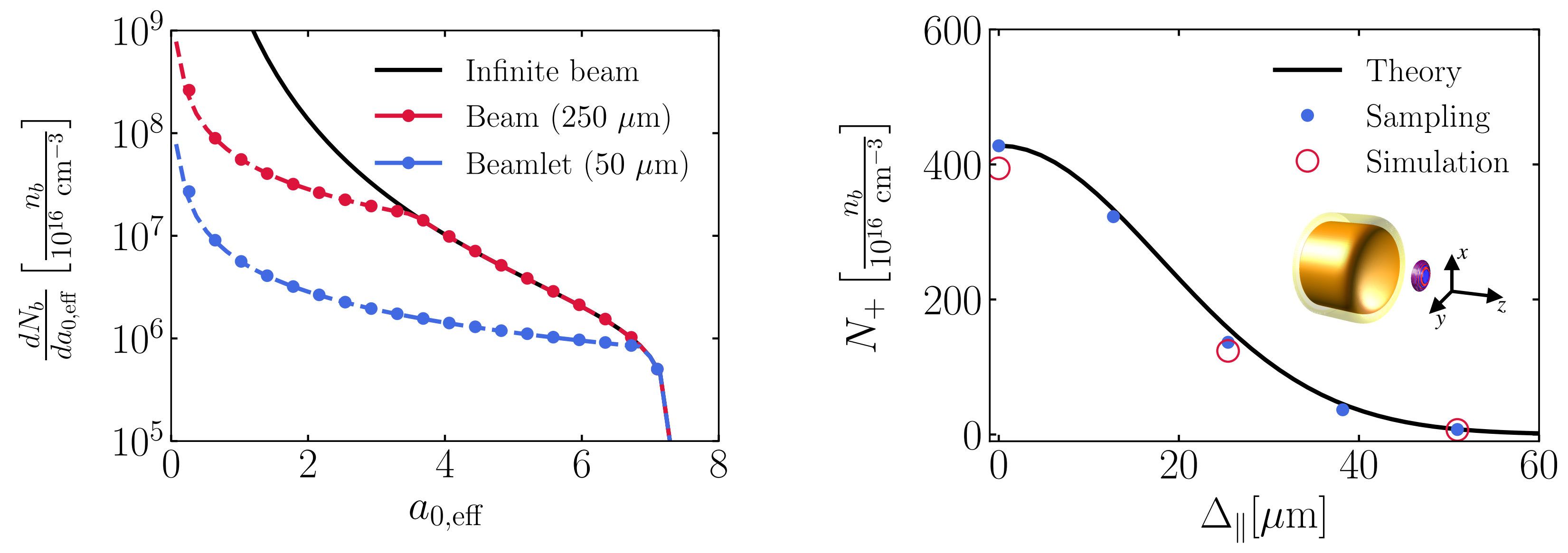

Figure 2: Particle distribution for a Wide beam and positron yield as a function of temporal misalignment

Optimal focusing

N_+^{PW} is a growing function of a_0 (at constant laser pulse energy $a_0 \propto W_0^{-1}$), and the number of seed electrons interacting with peak intensity $\propto W_0^2 z_R \propto W_0^4$.

There is a trade-off between using a short focal length to obtain the highest conceivable laser intensity, and having a wider interaction volume where more seed electrons participate in the interaction.

Using the previous particle distribution in $a_{0,\mathrm{eff}}$, we integrate the results numerically to find the optimal spotsize and maximum positron yield.

beam : $E_0 = 10$ GeV, $L = 200\ \mu$m, $n_b = 10^{16}$ cm^{-3} laser : $\lambda = 0.8\ \mu$m, $\tau = 150$ fs

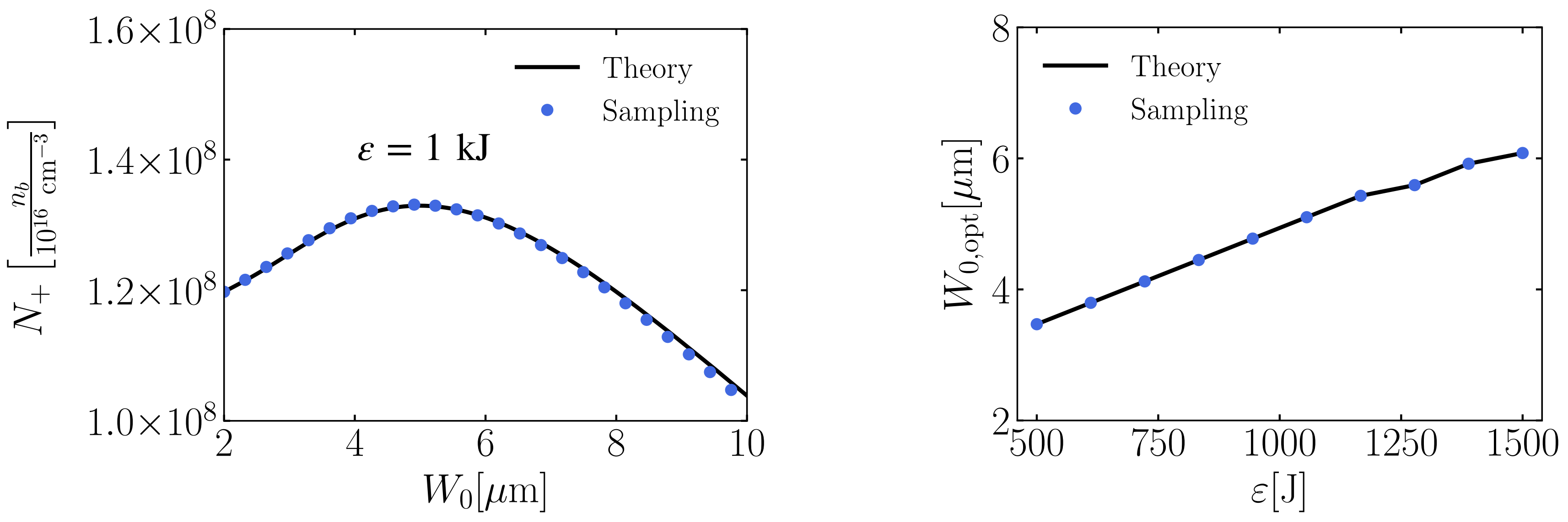

Figure 3: (left) Number of generated positrons keeping the total laser energy constant (right) Optimal laser spotsize as a function of the total pulse energy.

Parameter study for future laser facilities

For a particular laser system and an electron beam, one can find an optimal spotsize associated with the maximum number of positrons that can be produced per shot. Here we show a parameter study identifying optimal conditions for lasers below 1 kJ and pulse durations below 200 fs.

For a $\varepsilon = 1500$ J laser (500 J for e^- acceleration, 1000 J for scattering)

- ELI, $N_+ = 2.4 \times 10^8\ (n_b/10^{16}\ \mathrm{cm}^{-3})$ at $W_0 = 6.2\ \mu m$

beam : $L = 200\ \mu$m, $n_b = 10^{16}$ cm^{-3} laser : $\lambda = 0.8\ \mu$m, $E_0 = 13$ GeV

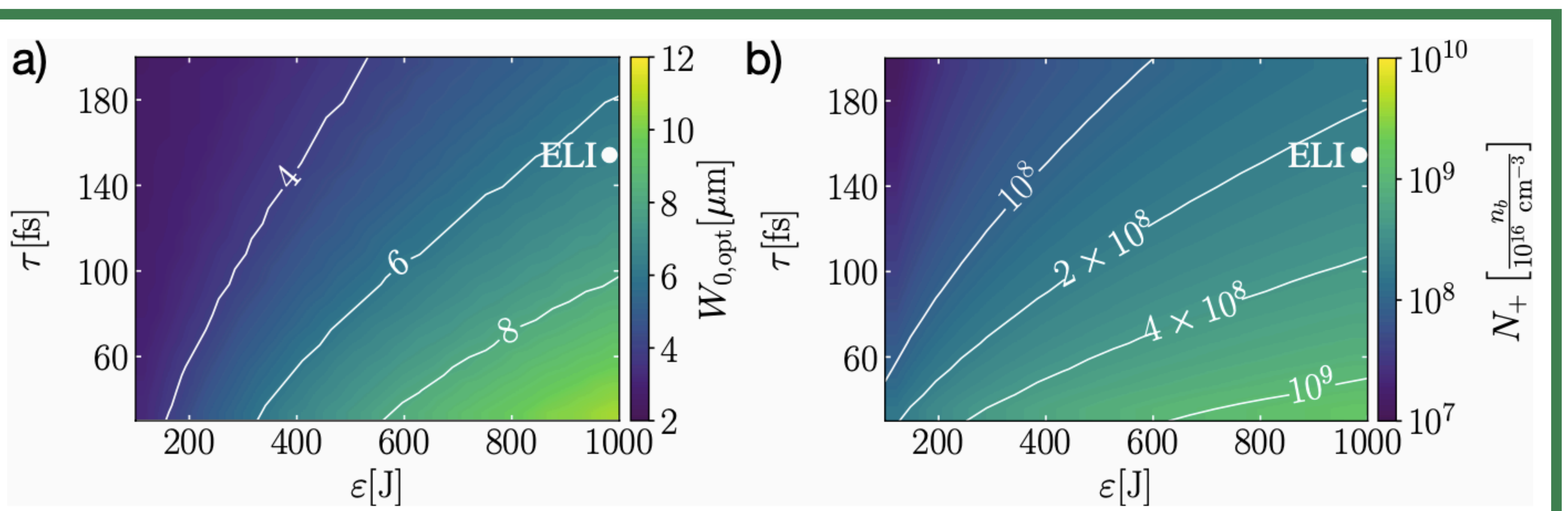

Figure 4: (left) Optimal laser focusing and (right) associated number of generated positrons

Conclusions

We have generalised a plane wave model for positron production in electron-laser scattering to include laser focusing, electron beam distribution and spatio-temporal synchronisation.

Our optimisation study shows that aiming at a very short focal length and highest possible laser intensity is not always the best option.

For more information about lasers with different pulse durations τ and other electron beam shapes that can be relevant for future experimental design please see Ó.Amaro and M.Vranic, submitted to NJP (2021), arXiv:2106.01877

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